Determination of small size bedload sediment transport and its related bedform under different uniform flow conditions

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Abstract: - A laboratory study has explored to determine the influence of current uniform flow conditions on bedload of different small size sediment particle beds and its bed formations. The influence of uniform flow and its related near bed turbulent flow conditions on bedload sediment transport and its related bedform in relatively low, mild and steep slopes channel has been experimentally investigated. Four sediment particle sizes were evaluated in the experimental study: (1) fine sand (0.2 mm), coarse sand (1.6 mm), very coarse sand (2.8 mm), and fine grain (4.4 mm).

A traditional experimental technique was developed to enable accurate performance for sediment particle transport measurement. The technique of estimating the transport rate of sediment particles is based on the trap measuring device. The trap was assessed for their efficiency by observation and photograph method. This enables the measurement of the area of the movable sediment particles to be determined by the collection of the particles in traps. The traps with an inlet width of 29 cm, a length of 15 cm and a height of 6 cm were selected to collect sediment particles. The sediment transport rates were then predicted using well known sediment transport equations.

This paper presents results from the laboratory study of the effects of various uniform flows on the bedload and its related bedform of the bimodal small sediment particle beds. The experiments are based on near bed turbulent flow forces on the bed resistance. The results show that the bedload and its related bedform are occurred by increasing the value of bed slope and the ratio of water depth to sediment particle size. The results obtained from the bedload and its related bedform present clearly the difference of four used material, which are necessary for computing the risk for different values of the particle Reynolds number.

Key-Words: - Bedload, bedform, sediment transport, sand, near bed turbulent flow, uniform current

1 Introduction

Water flows over erodible small size sediment particle beds provide a substantial interest in environmental fluid mechanics and geophysical studies. The suspended small size sediment particles in flows and those on the bottom surface, due to the effect of gravidity and turbulent flow, are still challengeable study. The essential importance in the context of sediment transport is to calculate the bed and suspended load transport capacity by integrating the velocity and relative concentration profiles along flow depth.

The most theory applied to the bedload and suspended sediment transport was achieved on open channel flow, which presumes uniform steady flow condition. Due to the practical importance of the bedload and its related bedform in the context of sediment transport many researchers began to attempt this problem as the first at the last few decades [1, 2]. The criterion for predicting the initial motion and sediment transport was derived from the experimental work of Shields (1936) who studied the initial motion of sediment in steady flow on a flat bed [3]. Shields presented a non-dimensional graphical values of grain Reynolds number, Re_d*, versus Shields parameter, $\tau*$. Yalin (1972) pointed out that the scatter of the experimental points on a Shields diagram is mainly due to the discrepancy in the determination of the critical stage and the fact that sediment with different geometric properties are plotted on the same coordinate system [4].

The influence of turbulence on sediment entrainment has been the subject of several studies; some of the earliest were the laboratory studies of

Grass; who demonstrated that entrainment of fine grains could be linked with observed turbulent flow features [5]. Drake *et al.* (1988) were one of the first studies to examine the motion of gravel particles at full scale as they were entrained from a gravel river bed [6]. Recent work of Nelson et al. (1995) suggests that bed shear stress does not accurately predict the bed load sediment transport rate [7]. The ratio of the inertia to drag force increases as the grain size increases. The assumption that the inertia force is negligible therefore may not be valid in environments with large grain sizes.

However, more recent work measured bedload, and flow characteristics over beds in relatively mild and steep slopes channel [8-11].

This study focuses on the understanding of the effects of uniform flow conditions on bedload of different small size sediment particle beds and its related bedform in the context of sediment transport. Initially the productions of the effected water depth and slopes on the bedload and its related bedform and transport rate during measurement times are investigated to confirm other predictions in the case of different uniform currents. The results present for slow, mild, and steep slopes within a range of 0.002 to 0.015.

2 Experimental set up

All experiments were carried out in the hydraulics laboratory. The flume itself is 7.5 m long, 0.3 m wide and 0.3 m high. It has glass walls and a steel floor to be covered with sediment. The floor of the flume can be modified for different purposes of as was done for this work. Two point gauges were made to measure the water level as a function of time along the flume especially at fixed bed area, because water level should not change on the fixed bed level during each measurement. They are digitally displayed the surface water level along the flume especially applying on the central section the flume. They were adjusted regularly before each experimental measurement series. Detailed information about the actual state of the flume showed in figure. 1.

Fig. 1, Detailed information about the armfield flume experimental measuring equipment

All experiments were thus run under plane washed and sieved bed conditions. A typical detail of the granulometry conducted is summarised in Table 1.

Table 1, principal information of the sediment particle characteristics for the experimental measurement

Bed material (sand)	Particle size, D_{ave}, (mm)	Density ρ_s, (Kg/m^3)	Porosity (%)	Water depth H, (mm)
Fine sand	0.2	2400	41	5-25 increment in Every 1mm
Course sand	1.6	2580	42	5-50 increment in Every 2mm
Very course sand	2.8	2600	43	10-105 increment in Every 2-5mm
Fine grain	4.4	2630	45	20-116 increment in Every 2-5mm

During measurements, the sediment particles fell through in the trap (as shown in the figure 1) without any supplied particle in the system. When the trap was almost full, the collected sediment particles were removed from trap and emptied into separate containers. Such sediment particles were left for a certain period to dry and subsequently count and weight. This recirculation procedure was repeated during each experiment.

The floor of the flume was modified for our experiments. A rigid bed of 2 m length from upstream end of the flume consisting of a single layer of the sediment particles (first half with D_{ave}=6 mm and the rest by D_{ave}=3 mm) glued to a wood floor was fixed onto the origin bed to develop a turbulent boundary layer and to obtain uniform flow on compatible to natural movable bed. The first 25 cm of the movable bed was contained by D_{ave}=5 and 1 mm transitional red coloured sediment particles to avoid an influence of possible local erosion effect due to different particle bed structures. Then the considerable movable bed was made up of sediment particles to be investigated, the thickness of this layer was about 6 mm from flume floor. The top opening for the trap was 30 cm by 15 cm. The downstream end of the trap were also made up of sediment particles of D_{ave}=5 and 1 mm transitional red coloured sediment particles and by length of 25 cm, to avoid an influence of possible local erosion effect due to free overflow on the traps.

A continuously accumulative sediment particle measuring device (figure 2) was designed, constructed and installed at the position around 500 cm from upstream inlet or around 300 cm from the downstream end of transitional red coloured movable bed material section of the flume. A typical photo of measuring device (trap) for collecting different movable bed sediment particles material is showed in figure 2.

Fig. 2, A typical photo of measuring device (trap) for collecting interested sediment particles such as fine sand (shown above), course sand, very course sand, and fine grain

Each trap consists of a four separate area to segregate the moved bed materials at certain time. When the trap was almost full, it was emptied and then adjusts it for further experiments.

Bed level was screeding and point gauges were also used to assess and level the movable bed before each experiment.

3 Experimental procedure

Before commencement of a series of experiments a number of operations were necessary: The sediment measurement device (trap) was checked and then emptied if necessary; a flow exceeding slightly the beginning of sediment transport into the flume for a short period, in order to arrange naturally the sedimentary bed.

Point gauges were adjusted for measuring flowing steady water level conditions. The range of water discharge used during experiments was imposed not only by the limited volume of the trap, but also by the range of erosion would be happened in the measurement system. When the required water discharge was fixed, uniform flow conditions were attained in the flume. During the experiment the water levels along the flume were measured using digital point gauges. When the sediment measuring device (trap) was full, the water discharge was decreased below the critical level or stopped the flow system. All collected materials in the trap was removed from the trap and then dried, counted and weighted for further analysis. The procedure of the sediment particle measurement due to action of water flow condition was repeated after each experimental measurement in the same manner as at the beginning of the experiment.

At steady flow conditions a total of 125 experimental measurements were carried out, sediment transport occurred in 110 cases, while in 21 experiments the flow was too weak to produce a measurable sediment transport.

4 Methodology and Presentation of experimental data result

Four sediment particle characteristics (Table 1) were chosen as a bed material, all sediment particle transport experiments were carried out for different slopes and for different water depths and discharges. The water stages were measured by point gauges along the flume. For further calculations the average water depth, h, from these measuring was used. It served also, after correction for wall effects, to calculate the hydraulic radius, $R_{h,}$ the discharge, Q, was determined and the bedload sediment particles was also obtained with sediment measurement device (figure 2). Time duration of each experiment was dictated by the reached equilibrium and the limited volume of the trap.

For each experiment, the recirculation flow was started at a very low flow rate to minimize the initial instability. Following each experiment, the sediment particle was collected and dried for the calculation of the bedload transport rate, q_b.

The corresponding bed sediment rating curves can be obtained by plotting of τ^* versus q_b^* for all used materials. Here τ^* and q_b^* are the dimensionless Shields stress and bedload parameter respectively defined as

$$\tau^* = \frac{\tau}{(\rho_s - \rho)\, g\, D} \qquad (1)$$

Where ρ_s is the sediment density, ρ is the fluid density, g is the gravitational acceleration, and D is the grain size. The corresponding bed shear stress, τ, is determined from ($\tau = \gamma. R_b .S_0$). Where γ is unit weight of water; R_b is hydraulic radius adjusted for the effect of the flume walls in accordance with the procedure presented in Shvidchenko and Pender (2000a) [12]; and S_0 is slope of the flume for uniform flow over the test section. Similar behaviour was detected in the experimental data collected by Shvidchenko and Pender (2000b) [13] for uniform sediments and sediment mixtures Shvidchenko et al. (2001) [14]. The observed phenomenon can be explained in terms of the effect of relative roughness, which for a given bed material and a given bed shear stress causes greater friction resistance and, consequently, lower transport at steeper slopes.

The sediment rating curves were used to determine values of critical Shields stress τ_c^* for different slopes corresponding to the reference transport rate $q_b^* = 10^{-4}$ (which is equivalent of $I = 10^{-4}$ s^{-1}). The obtained values of τ_c^* are plotted against grain Reynolds number Re_* together with the corresponding slopes. It is seen that the present data are in overall agreement with the threshold diagram of Shvidchenko and Pender (2000b) indicating that the critical Shields stress for motion of uniform sediment depends not only on grain size, but also on bed slope (correlated with relative roughness).

According to the experimental data of Shvidchenko and Pender (2000a), this transport intensity is equivalent to the reference transport rate $q_b^* = 10^{-4}$, where q_b^* is the dimensionless bedload parameter expressed by

$$q_b^* = \frac{q_b}{\rho_s \sqrt{(s-1)\, g\, D^3}} \qquad (2)$$

in which q_b is the bedload transport rate per unit width (dry weight), and $s = \rho_s / \rho$ is the specific gravity of sediment. The reference transport rate $q_b^* = 10^{-4}$ can be used as a substitute for the reference transport intensity $I = 10^{-4}$ s^{-1} to define threshold conditions in situations where data on the number of displaced bed particles is unavailable.

The methodology used for quantifying initiation of sediment motion was originally developed by Shvidchenko and Pender (2000a). This methodology uses an arbitrarily defined reference value of transport intensity is defined as

$$I = \frac{m}{M\, T} \qquad (3)$$

where m is the number of particle displacements during the time interval T from the mobile bed area A, and M is the total number of surface particles in this area, defined as

$$M = \frac{(1-p)\,A\,D}{\frac{\pi\,D^3}{6}} \tag{4}$$

Where, p, is the bed porosity and, A, is the area of interest. The reference transport intensity of $I = 10^{-4}$ s^{-1} adopted by Shvidchenko and Pender (2000a) is used in this study as representative of the threshold of sediment movement, for more details see [15].

The methodology developed by Shvidchenko and Pender (2000a) eliminates the subjectivity in defining threshold conditions and provides for consistency of the results and comparability of different data sets. The method of relating threshold of sediment transport intensity as a measure of streambed threshold conditions. The sediment motion with a small sediment transport rate is widely used for studying incipient motion of graded sediments (e.g. Parker et al. 1982, Wilcock 1993, Kuhnle 1993, Andrews 2000) [16-19] but, surprisingly, has rarely been applied to uniform sediments.

In this paper the experimental tests had durations of up to 140 hours, limited by the development of bed forms or when a sufficient amount of sediment had accumulated in the collection measuring devices. Upon completion of a full set of tests for a given sample, the sediment was removed from the flume and the test section was prepared for the next sediment samples. Suspended particle transport was observed only for very fine sand in very rare case of the experiments, erosion option, which normally was out of the range of the experimental tests.

The collected experimental data has been analysed by applying above mentioned methodology and related calculations.

Table 2, typical summary of collected data test series including related calculation for sediment transport for uniform flow in armfield flume experiments

No	**Slope** j, x10-3	**Width** b, m	**Depth** h, m	**Time** T, s	**Dry weight**, G, Gr	**Transport rate**, qb, Kg/smxE-6
1	7	0.3	0.02	1800	0	0
2	7	0.3	0.02	3600	0.24	0.222
3	7	0.3	0.03	5400	1.41	0.8704
4	7	0.3	0.03	7200	16.85	7.801
5	7	0.3	0.04	7200	244.7	113.31
6	7	0.3	0.04	1800	847.7	1569.9

Table 3, typical summary of collected data test series including related calculation for bedload parameter and transport intensity for uniform flow in armfield flume experiments

Numb. of mov. m, No	**Effe. len.** l, m	**Area of mob. Bed** Am=bxl, m2	**part. in a mob. bed** N, No	**Tran. inten.** I, No/s, X10-6	**Bedl. para.** q*b xE-7
0					
5	0.005	0.0015	212.04	6.55	1.45
37	0.015	0.0045	636.13	10.77	5.7
390	0.12	0.036	5089	10.64	51.11
5573	1.2	0.36	50890	15.21	742.44
19302	2.4	0.72	101780.84	105.36	10286.4

5 Results and discussion

Based on methodology and procedure of data analysis mentioned above (section 4), the following main results have been focused and presented in this paper.

5.1 sediment transport analysis during measuring time

In this research the flow depth in the experimental armfield flume was up to 12 cm, measured using two point gauges to investigate the effect of stream-wise uniform flow on bedload sediment transport during experimental measurements. The tilting flume was set for all tests with several bed materials and slopes. Water depth, bed slope, and related measuring time have great effect on the variation of transport rate despite particle size.

The results for natural uniform fine sediment (D_{ave}=0.2 mm) particles are presented first herein. The very fine sand sediment transport rate has been investigated for low and mild bed slopes. The fine sediment transport rate has been plotted with respect to various water depths up to 3 cm as shown in figure 3. This figure shows the influence of various very low water depth and low bed slope on fine sediment (D_{ave}=0.2 mm) particles. The figure 3 shows the oscillatory variation of transport rate by applying various very low water depth and low bed slope during experiments.

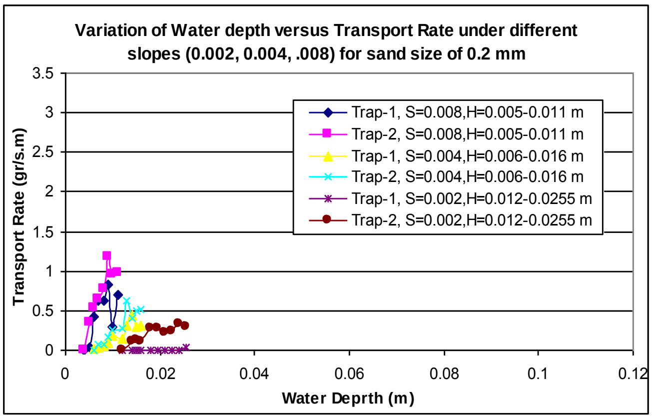

Fig. 3, Variation of transport rate of fine sand sediment particle (D_{ave}=0.2 mm) versus uniform flow depth for different slopes during measuring time

The result shows that the transport rate increased by increasing only water depth until equilibrium. Also by increasing bed slope the uniform fine sand sediment transport rate increased sharply.

The results for fine sediment (D_{ave}=1.6 mm) particles are presented second herein. The fine sand sediment transport rate has been considered for various bed slopes. The result shows that the transport rate reduced by reducing slopes as shown in figure 4. The figure also shows the significance of the bed slope on the variation of transport rate versus water depth. The figure 4 also shows less curvature of transport rate by applying various water depth and bed slope during experiments.

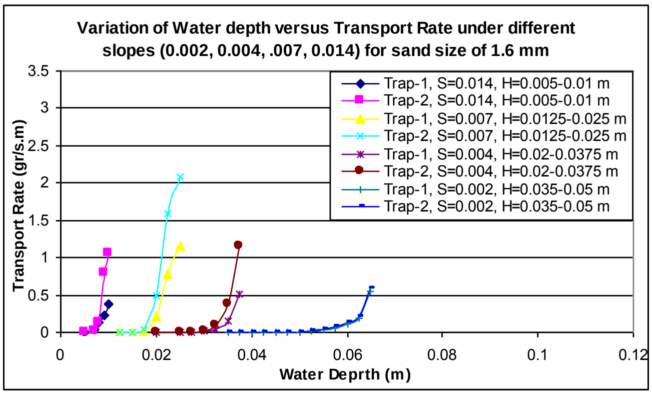

Fig. 4, Variation of transport rate of course sand sediment particle (D_{ave}=1.6 mm) against uniform flow depth for different slopes during measuring time

The results for course sand sediment (D_{ave}=2.8 mm) particles are presented third herein. The course sand sediment transport rate has been examined for various water depths and bed slopes. The result shows that the transport rate reduced by reducing slopes as shown in figure 5. The figure also shows the significance of the bed slope on the variation of transport rate versus water depth. The figure 5 also shows less curvature of transport rate by applying various water depth and bed slope during experiments.

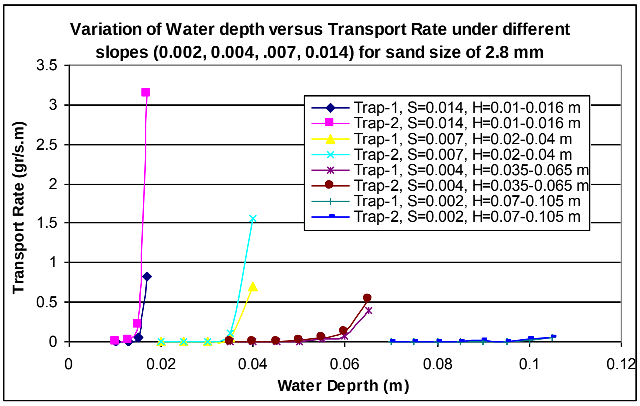

Fig. 5, Variation of transport rate of very course sand sediment particle (D_{ave}=2.8 mm) versus uniform flow depth for different slopes during measuring time

The results for fine grain sediment (D_{ave}=4.4 mm) particles are presented fouth herein. The fine grain sediment transport rate has been considered for various bed slopes. The result shows that the transport rate reduced by reducing slopes as shown in figure 5. The figure also shows the significance of the bed slope on the variation of transport rate versus water depth. The figure 5 also shows quite linearity of transport rate by applying various water depth and bed slope during experiments.

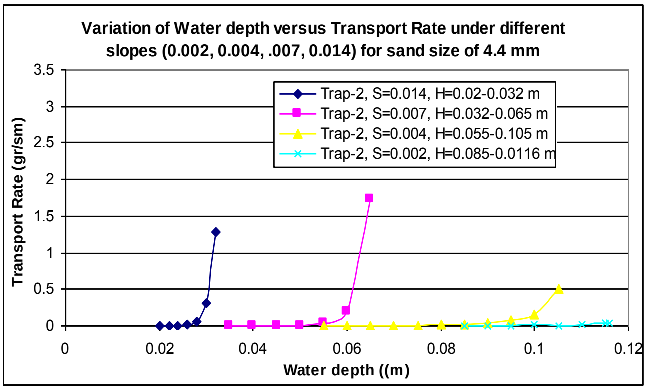

Fig. 6, Variation of transport rate of fine grain sediment particle (D_{ave}=4.4 mm) against uniform flow depth for different slopes during measuring time

5.1 Bedload sediment transport and its related bedform during measuring time

The bedload and its related bedform of small sediment particles have been explored by photographing and plotting the bedload parameter and transport intensity during time measurement. The results were achieved for the water depths of 0.4-11 cm and the flume slopes of 0.002-0.014.

Figure 7 shows the bedform with an unsymmetrical ripple obtained from bed fine sand (0.2 mm). The variation of bedload parameter and transport intensity during experiments for the same fine sand is showed in Figure 8.

Fig. 7, A typical photo of the bedform obtained for bed with very fine sand water worked

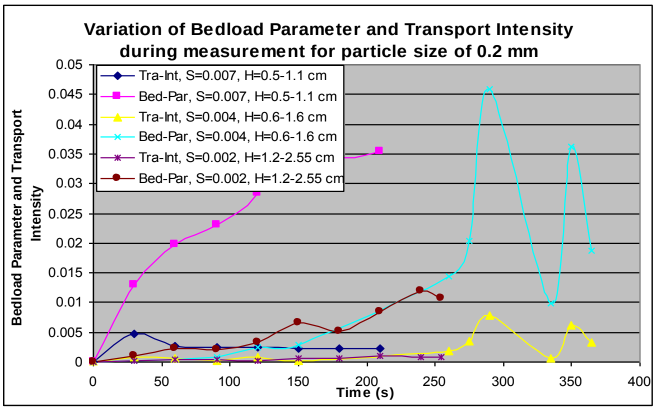

Fig. 8, Variation of bedload parameter and transport intensity over a period of time for different bed slope with fine sand

The natural fine sand bedload parameter and transport intensity during the experiment was found comparable with bedform digression. Which it means when the bedform is rippled the bedload parameter and transport intensity during the experiment will be osilated and inverse.

Figure 4.1 and 4.2 show the variation of transport rates for particle sizes bigger than 1 mm. The results illustrate the increments of transport rates during experiments. In each experiment the slope remains constant but the water depth is increased by increments of 1-5mm. On the other hand, the figure 4.3 shows that the transport rates are varied during experiments for the fine sand, smaller than 1 mm. This means the transport rates for the natural particle sizes less than 1 mm are different compared to bigger particle sizes. The results were obtained for different water depths and bed channel slopes.

The results for the course sand particle size (1.6 mm) are presented next herein. Figure 9 shows a typical photo of bedform with slightly unsymmetrical ripple. The bedload parameter and transport intensity obtained from the course sand over a period of time for different bed slopes shows in figure 10. The result illustrates the increments of bedload parameter and transport intensity during experiments none linearity as its related bedform moderately changed.

Fig. 9, A typical photo of the bedform obtained for a bed with course sand water worked

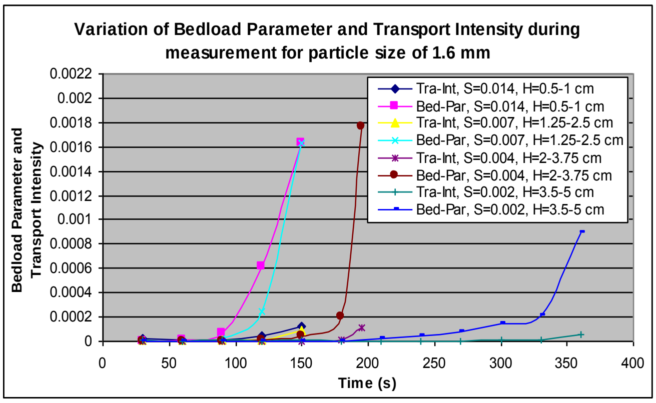

Fig. 10, Variation of bedload parameter and transport intensity over a period of time for different bed slope with course sand

The above results also show that the required time for starting bedload and its related bedform of course sand is longer than the smaller size. Which it means by reducing the particle size, the required time for the bedload and its related bedform decreased.

The results for the very course sand particle size (2.8 mm) present as follows. Figure 11 shows a typical photo of bedform which illustrates unaffected bed as described above for other materials. The result obtained for the very course sand shows the variations of bedload parameter and transport intensity during measurements for different bed slopes in figure 12.

Fig. 11, A typical photo of the bedform obtained for a bed with very course sand water worked

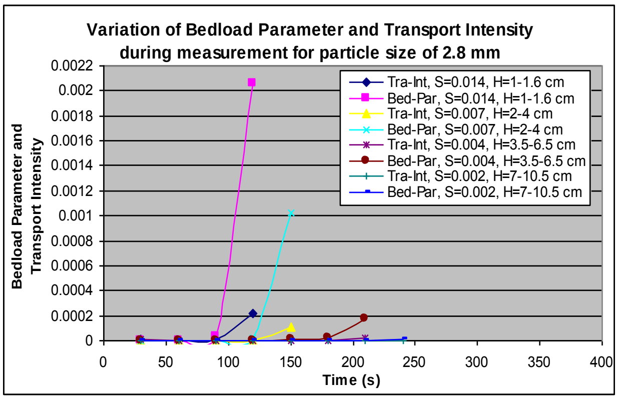

Fig. 12, Variations of bedload parameter and transport intensity over a period of time for different bed slope with very course sand

Finally, the results for the fine grain particles (4.4 mm) represent as follows. Figure 13 shows a typical photo of bedform which illustrates unaffected bed as described above for other materials. The result for the fine grain particles illustrates the increments of bedload parameter and transport intensity during experiments as shown in figure 14. This figure shows that the bedload parameter and transport intensity over a period of time varies linearly as its related bedform unchanged clearly. The result also shows that by increasing the particle size, the required time for starting bedload and its related bedform increased. The figure 14 shows that by increasing the used sediment particle size the value of bedload parameter and transport intensity are reduced for over a measuring time.

Fig. 13, A typical photo of the bedform obtained for a bed with fine grain water worked

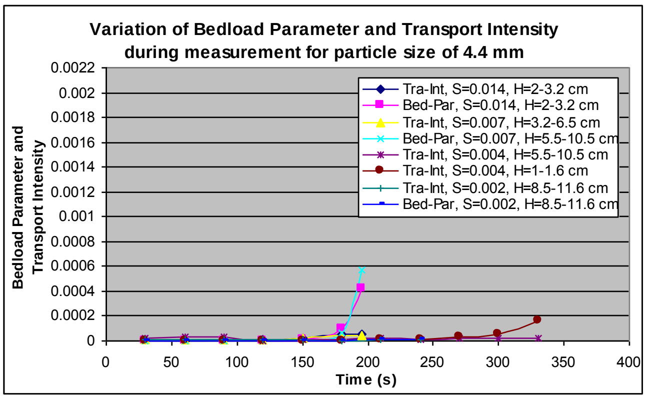

Fig. 14, Variations of bedload parameter and transport intensity over a period of time for different bed slope with fine gain

6 Conclusion

The bedload of different small size sediment particle transport and its bed formations were experimentally investigated. An existing laboratory facility (figure 1) was modified in a way that the determination of the particle sediment transport is continuous and accurate. The most important part of the measurement system was the development of a traditional sediment particle measuring device (figure 2).

The results which are presented the bedload of different small size sediment particle transport rate versus water depths in figures 3-6 showed clearly the difference of the four used material under different slopes and uniform flow conditions. The results show that by increasing the four sizes used material the variation of transport rate versus water depths are changed from curvature to linear forms. Which it means the fine particles are constructed curvature sediment transport rate against water level but, fine grains are generated quite linear forms. They are also represented a good concept agreements between the bedload and its related bedform for each sediment particle beds.

The results which are presented the bedload and its related bedform in figures 7-14 are based on bedload parameter and transport intensity over a period of time. They showed clearly the difference of the four used material under different slopes and uniform flow conditions. They are represented a good concept agreements between the bedload sediment transport rate and its related bedform for each sediment particle beds. The figures show that the value of bedload parameter and transport intensity is reduced as the used sediment particle size increased during measuring time.

The results obtained for the fine sand show that the structure of the results is completely different from other used materials. For example, the fine sand particle beds shows that the bedload and its related bedform is taking place from ratio of water depth to particle size more than 25, $h/D_{ave}>25$. On the other hand, The results for other used materials show that the different effect on the bedload and its related bedform is occurred by increasing the value of bed slope over than $S_0=0.002$ and ratio of water depth to particle size more than 40 ($h/D_{ave}>40$). The above described results were verified by observation for a limited and random range of moving sediment particles.

The results of the present investigation should be useful for engineers designing channels or gullies in mountainous regions, where large slopes and small relative depths are frequently encountered.

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